

Mon. Not. R. Astron. Soc. **000**, 000–000 (1999)

Variability of the extreme $z=4.72$ blazar, GB 1428+4217

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5 July 1999

ABSTRACT

We report X-ray and radio variability of GB 1428+4217 which confirm its blazar nature. IR observations reveal a powerful optical–UV component, not obscured by dust, which is suggestive of the presence of a billion solar mass black hole, already formed by $z \sim 5$. A detailed comparison of the broad band spectral properties of GB 1428+4217 with those of nearby blazars shows it to be extreme, but nevertheless consistent with the trend found for nearby sources.

Key words: quasars:individual (GB 1428+4217) – X-rays:quasars

1 INTRODUCTION

At redshift $z = 4.72$, GB 1428+4217 is the most distant X-ray source known (Hook & McMahon 1997; Fabian et al 1997; 1998). Its bright X-ray flux, of about 3×10^{-12} erg cm⁻² s⁻¹ in the 2–10 keV band, and radio flux, of about 100 mJy at 15 GHz, strongly suggest that the object is a blazar pointed toward us. The previous observations did not however clearly show the flux variability which is common to blazars. We have therefore observed GB 1428+4217 again in X-rays with the ROSAT HRI and have monitored it for several months with the Ryle radio telescope. We report here on our discovery of the expected X-ray and radio variability. We also now make a detailed comparison of its properties with those of nearby blazars.

2 ROSAT AND RADIO VARIABILITY DATA

GB 1428+4217 was observed 4 times with the ROSAT HRI during 1997 December and 1998 January. The source is very clearly detected each time and shows significant variability (see Fig. 1 where we include the earlier HRI point from 1996). It varied by a factor of about two over a timescale of two weeks (or less), which corresponds to less than 2.5 days in the restframe of the source. We note that previous ASCA and serendipitous ROSAT detections of the source give a flux consistent with that of 1996 July.

The Ryle Telescope at Cambridge was used to monitor the flux density of GB 1428+422 at 15 GHz on about 50 occasions between 1998 April and December (unfortunately

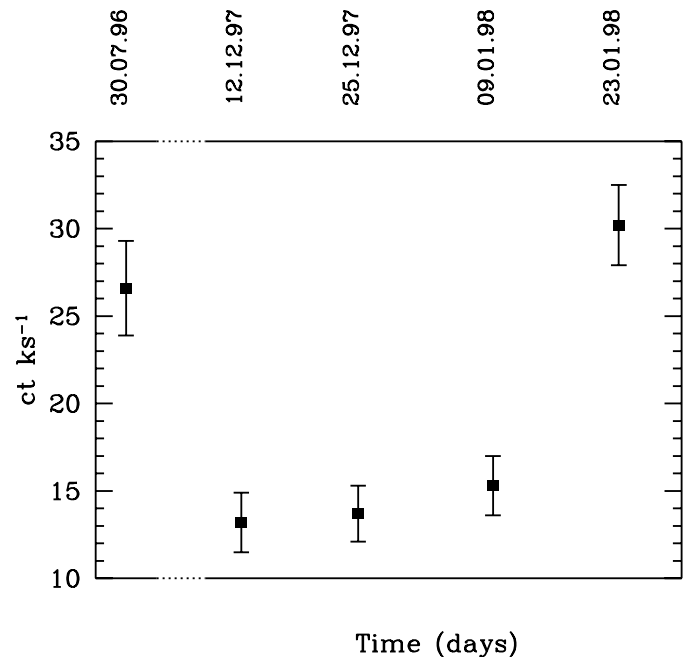


Figure 1. Significant count rate variability can be inferred between the five different ROSAT HRI observations during 1996, 1997 and 1998. Dates are indicated on the top of the plot, and the corresponding exposure times for the 1997 and 1998 datasets are 4.8, 5.9, 5.8 and 6.2 ks, respectively. As a reference point, 27 ct ks⁻¹ correspond to 10^{-12} erg cm⁻² s⁻¹ in the (0.1–2.4 keV) ROSAT band.

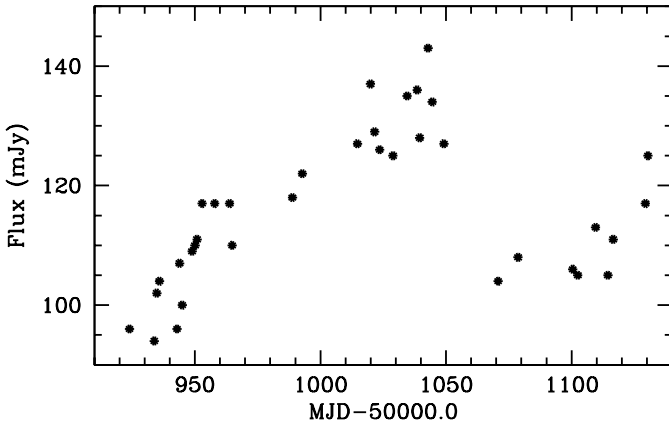


Figure 2. Radio light curve at 15 GHz, showing the significant variability of GB 1428+422.

much later than the HRI pointing). These observations, usually of short duration (typically < 1 h), were made during gaps in the regular schedule of the telescope. A more detailed description of the observing technique is given in Pooley & Fender (1997). The flux-density scale of the observations was established by a nearby observation of either 3C 48 or 3C 286. Similar datasets have shown that the overall calibration in such cases has an r.m.s. scatter of less than 3 per cent.

In Fig. 2 the flux density of GB 1428+422 is plotted: significant variability can be detected with an amplitude of ~ 40 per cent over about three months, and ~ 15 per cent on timescale of ten days.

We therefore conclude that the significant variability on short timescales detected both in the X-ray and radio bands strongly confirms the identification of GB 1428+4217 with a blazar. In the following we will then consider the variability and spectral properties of this source, and compare them with those of nearby blazars, with the aim to gain insight both on the physics and evolutionary behavior of this class of AGN.

3 INFRARED OBSERVATIONS

In addition to the broad band B and R magnitudes (and monochromatic continuum flux at a rest frame wavelength of 1500\AA) reported by Hook & McMahon (1998), we present here J , H and K observations. They were carried out on 1997 March 26 with the United Kingdom Infra-Red Telescope (UKIRT) using the 256^2 InSb array based camera IRCAM3 in the 0.28arcsec/pixel mode with exposure times per waveband of 900 s. The data underwent dark subtraction, flat-fielding, and mosaicing of the dithered images using the Starlink IRCAMDR software. Photometry was carried out using apertures of diameter 5 arcsec calibrated against similarly analyzed standard stars from Casali & Hawarden (1992). In Table 1, we list the observed magnitudes and derived fluxes.

The spectral index over the range covered by the optical and IR data is ~ 0.0 ($F_\nu \propto \nu^{-\alpha}$). This is bluer than the canonical α_{uv} of 0.7 (eg. Fall, Pei & McMahon 1989) which

means that there is no evidence for reddening over the rest frame spectral range $1500\text{--}4000\text{\AA}$.

4 VARIABILITY CONSTRAINTS

The spectral energy distribution (SED) of this source already pointed towards its identification with a blazar (Fabian et al. 1997, 1998). In particular, Fabian et al. (1998) showed that the (poorly sampled and not simultaneous) SED of GB 1428+4217 can be accounted for as non-thermal synchrotron and inverse Compton emission from a relativistically moving source, forming two broad peaks in $\nu F(\nu)$, as characteristic of blazars. However, no constraints on its size were available at the time. The X-ray variability timescale inferred from our ROSAT observations sets instead a significant upper limit on the dimension. We therefore re-consider the modeling of the SED and find that a broad band energy distribution and flat X-ray spectrum consistent with the data can still be found adopting a simple homogeneous model. As an example of the results obtained, in Fig. 3 we show the SED from one of the specific models (see caption) proposed by Fabian et al. (1998), where the intrinsic dimensions and Doppler factor are of order $R \sim 5 \times 10^{16}$ cm and $\delta \sim 20$, respectively. As already pointed out by Fabian et al. the parameters inferred from the modeling are globally consistent with those deduced for larger samples of blazars at lower redshifts (Ghisellini et al. 1998).

A further hint that beaming is involved is given by the rate of change of luminosity, $\Delta L/\Delta t \gtrsim 5 \times 10^{41}$ erg s $^{-2}$. The simple efficiency limit (Fabian 1979; Brandt et al. 1999) then yields a radiative efficiency for the source $\gtrsim 20$ per cent if only the luminosity in the ROSAT band is considered, and about ten times higher if one consider the total X-ray luminosity.

5 BROAD BAND SPECTRAL ENERGY DISTRIBUTION

A closer comparison can now be made between the spectral properties of GB 1428+4217 and those of nearby blazars. Differences can give important hints on the evolution in the intrinsic or environmental properties of radio-loud AGN.

Here we consider as quantitative SED indicators the broad band spectral indices^{*}, α_{ro} , α_{ox} and α_{rx} .

Because of the uncertainties due to the flux variability we estimate the range spanned by α_{ro} , α_{ox} and α_{rx} , by considering the extremes of the observed radio and X-ray flux ranges. The two areas in Fig. 4 are representative of the intervals obtained. In this same figure, the spectral indices derived for GB 1428+4217 are compared with those obtained for complete samples of BL Lac objects and flat spectrum radio quasars (FSRQ; see Fossati et al. 1998 for details). Other two $z > 4$ blazars, GB1508+5714 at $z = 4.3$ (Moran & Helfand 1997) and RXJ 1028.6-0844 at $z = 4.28$ (Zickgraf et al. 1997), appear similar to GB 1428+4217, subject to the uncertainty in the necessary optical K-correction for these objects (we adopt an optical spectral index for them of 0.7).

^{*} where the quasar restframe radio, optical and X-ray monochromatic fluxes are calculated at 5 GHz, 5500\AA and 1 keV.

Table 1. Infrared observations

Band	Wavelength Observed (μm)	Wavelength Rest (\AA)	Magnitude	Zeropoint [†] $\text{erg cm}^{-2} \text{Hz}^{-1}$	Flux mJy
J	1.22	2140 \AA	18.6 \pm 0.1	1.57×10^{-20}	5.7×10^{-2}
H	1.63	2860 \AA	18.0 \pm 0.1	1.02×10^{-20}	6.4×10^{-2}
K	2.19	3840 \AA	17.5 \pm 0.1	6.36×10^{-21}	6.3×10^{-2}

Notes: [†] Effective wavelengths and zero point fluxes on the α -Lyrae magnitude system from Bessel & Brett (1988).

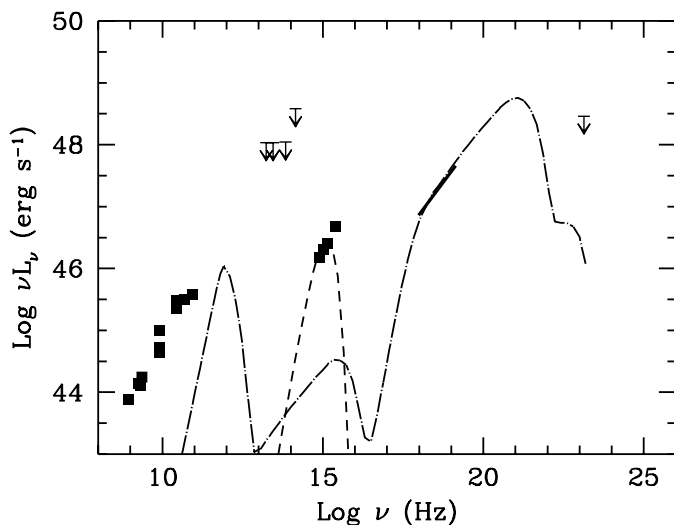


Figure 3. Broad band spectral energy distribution (data are not simultaneous). Superposed is the predicted SED from a homogeneous model, for a Doppler factor $\delta \sim 20$ and an intrinsic source typical size $R \sim 5 \times 10^{16}$ cm, while the other model parameters are the same as in Fabian et al. (1998) (EC model). The dashed peaked component represents the possible contribution by an external soft radiation field, which provides the seed photons for the inverse Compton high energy emission. The X-ray spectrum is derived from the ASCA data (flux level comparable with the ROSAT HRI 1996 observation).

These three sources lie apart from the nearby FSRQ reported. They do however follow the general trends which hold for the entire blazar class. It has been pointed out that if blazars are considered according to their total (and radio) power, then the presence/luminosity in (broad) emission lines correlates with the shape of the SED. In particular, the position in energy of the two broad continuum peaks and their relative intensity (power in the low energy component with respect to that in the high energy one) decrease with increasing total source power. This also translates into an increase of the α_{ro} and α_{rx} spectral indices, and a flattening of the latter at the highest luminosities (see Fossati et al. 1998). Note indeed that GB 1428+4217 follows these trends in the spectral index plane as predicted by its radio power. An interesting consequence is that one would expect

the synchrotron peak to be located in the mm band, well below the apparent optical peak of the (sparse) SED shown in Fig. 3.

Although the behaviour of GB 1428+4217, and the other two $z > 4$ blazars, fit the blazar scenario just described, the X-ray luminosities of the sources still exceed those predicted by the above correlations; the values of α_{ox} are significantly flatter than expected for the given source powers. Two caveats should however be remembered, namely the critical role of variability when discussing properties of blazars, and the possible influence of selection effects in detecting X-ray emission from GB 1428+4217. Indeed, a similar object with less extreme X-ray luminosity (fully consistent with the trends discussed above) would not have been followed up so readily in the X-ray band. Similar considerations apply for the other two high redshift objects, although we stress that the uncertainties in the (radio, optical and X-ray) spectral slopes of these two sources is large.

We now consider the implication of these results. Within the most widely accepted blazar scenario the two peaks of the SED are interpreted as due to synchrotron (the low energy component) and inverse Compton (the high energy one) processes. Although the nature of the seed photons [internal/synchrotron (SSC) vs external radiation field (EC)] is still not fully settled, evidence has been found that the source power is directly linked to the magnitude of the external radiation field, thus implying the increasing importance of the EC mechanism over the SSC one with increasing power. This also means more effective radiative cooling of electrons (by inverse Compton) - and thus a possible interpretation of the lowering of the energy of particles which emit at the peaks - and an increase in the relative importance of the Compton spectral component (Ghisellini et al. 1998).

If so, GB 1428+4217 (and maybe the other two high redshift quasars) represents a powerful source with an intense (or even extreme) external radiation field. This does not seem to be supported by the lack of very luminous emission lines (the photon field of which could be an important contributor to the external seed field).

However, there is interesting evidence for an intense optical-UV continuum flux, which cannot be easily interpreted as non-thermal emission. It seems plausible that this component (and that responsible for the intense Compton

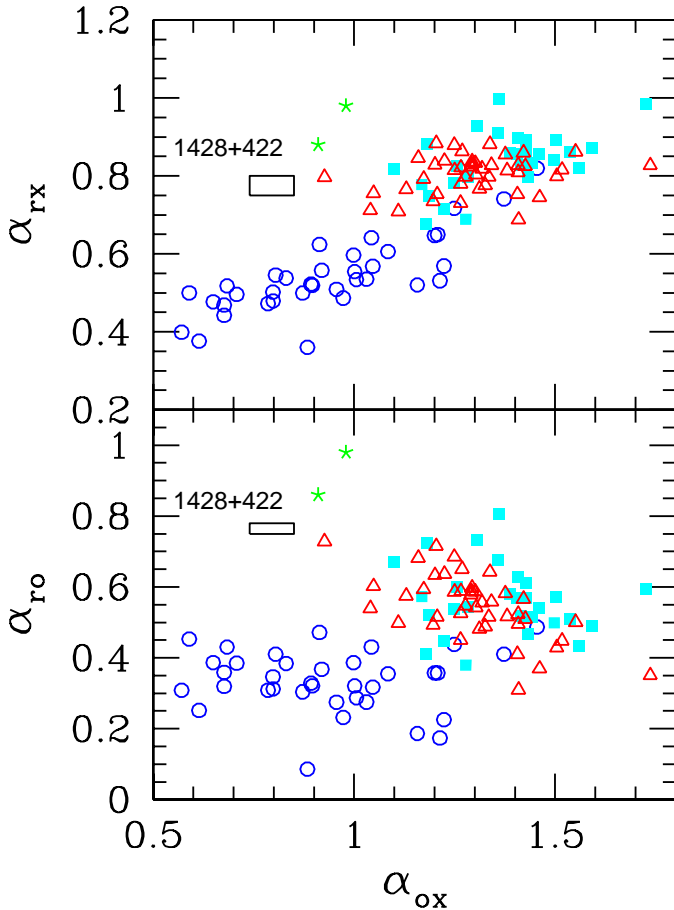


Figure 4. Broad band spectral indices for complete samples of radio-loud quasars (squares) and BL Lac objects (open circles and triangles), from the Wall & Peacock 2 Jy sample (Wall & Peacock 1985; Padovani & Urry 1992), the 1 Jy and Einstein Slew survey BL Lac samples (Stickel et al. 1991; Stickel, Meisenheimer & Kühn 1994; Perlman et al. 1996), respectively. GB 1428+4217 spectral indices, estimated considering the variable radio and X-ray observed fluxes, span the range indicated by the boxes. The stars refer to the other two $z > 4$ objects (GB 1508+5714 and RXJ 1028.6-0844), whose optical spectral index is assumed ~ 0.7 .

emission) have a nuclear origin. In fact no other radiation field (e.g. any plausible star cluster, or the cosmic microwave background) seems to be energetically relevant. It is possible that this component is analogous to the excess optical-UV emission in nearby quasar and might be ascribed to thermal dissipation from accreting material, which would itself contribute to the local external radiation field.

Independently of its origin it should be stressed that the detection of this optical component sets extremely tight limits to the presence of any dust along the line of sight to this high z source.

6 DISCUSSION AND CONCLUSIONS

Evidence for X-ray and radio variability in GB 1428+4217 confirms the blazar nature of this quasar.

Interestingly and perhaps surprisingly, the properties of such an extreme high redshift source seem to fit globally

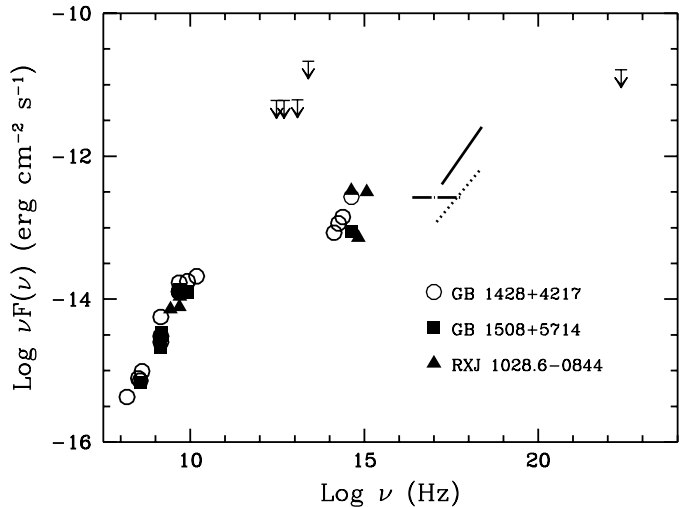


Figure 5. The SED of three $z \gtrsim 4$ radio-loud quasars are compared. The objects show a similar broad band behavior, with extreme flat X-ray spectral indices, low energy synchrotron and (plausibly) inverse Compton peaks. The continuous, dotted and dot-dashed lines reproducing the X-ray spectra refer to GB 1428+4217, GB 1508+5714 and RXJ 1028.6-0844, respectively. The X-ray spectrum of GB 1428+4217 is from the ASCA data.

the scenario for low redshift blazars. Although no conclusive evidence of peculiar intrinsic or environmental conditions can be found, there is some indication of even more extreme Compton cooling which might be associated for example with an unusually high external radiation field.

While no conclusions can be drawn on this basis, the issue remains open. Are all high redshift blazars characterized by such high (X-ray) luminosities? In Fig. 5 we show the broad band energy distributions of GB 1428+4217 and the two other $z > 4$ radio-loud blazars, GB 1508+5714 and RXJ 1028.6-0844. These are also characterized by a very flat X-ray spectral index and the broad band properties of luminous objects, and at least GB 1508+5714 might share with GB 1428+4217 such an extreme X-ray brightness. Broad band spectral coverage and variability studies of a significant number (possibly a complete sample) of such ‘primordial’ blazars are required.

We finally note that if indeed the detected optical-UV flux can be ascribed to a thermal component produced in the accreting process, a bolometric luminosity of $\sim 10^{47}$ erg s $^{-1}$ requires the presence of a black hole with billion solar masses, if accreting at the Eddington rate, which has to be formed by $z \sim 5$ (Efstathiou & Rees 1988). Furthermore, one can speculate that if the black hole mass is related to the mass of the galactic bulge according to the relation suggested by Maggiorian et al. (1998), a $\sim 10^{11} M_{\odot}$ bulge component has also to be present. Clearly the observational confirmation or rejection of these possibilities is of crucial importance for the study of galaxy and black hole formation and their mutual relationship.

Acknowledgments

We thank Gabriele Ghisellini for the use of the code for the homogeneous emission model. The Royal Society (ACF, RGM), the Italian MURST (AC), PPARC (KI) and the NASA LTSA Program (WNB) are thanked for financial support. This research was supported in part by the National Science Foundation under Grant No. PHY94-07194 (AC).

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